The Usual Suspects: Troubleshooting Anomalous UHF Relay On Mars Reconnaissance Orbiter In Time For InSight Entry Descent Landing

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337 Flight Communications Systems

21 Feb 2019

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Acknowledgements

Many contributed to this anomaly investigation

MRO Team
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Rachel Kim
Christina Kneis
Andy Kwok
Ryan Lim
Mazen Shihabi
Reid Thomas
Bruce Waggoner
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Andy Mishkin
Ryan Mukai
Pegah Pashai
Jack Quade
Emma Young

Mars Program Office
Chad Edwards
Roy Gladden
Hoppy Price

External Teams
MRO Flight Engineering Team (LM)
MAVEN (GSFC & LM)
Trace Gas Orbiter (ESA)

Executive Summary & Timeline

UHF relay passes between MRO and MSL started returning anonymously low data volumes starting July 2018 (around the peak of the 'global' Mars dust storm). Anomaly occurrence was sporadic and initially sparse. MRO, Electra, and other teams worked quickly to isolate root cause and propose corrective action. MRO successfully recorded telemetry from InSight EDL and has been anomaly free since implementation of corrective action

7/3/18	First set of bad passes (4 in 3 days)	172 passes
9/17/18	Next set of bad passes (2 in 1 day)	
10/3/18	Next set of bad passes (4 in 4 days)	
10/9/18	MPO convenes anomaly investigation team	
10/13/18	MSL starts modifying relay operations to support investigation	
10/24/18	MRO begins BER / Sniff tests	
10/30/18	First instance of anomaly onset part way through pass	
	- Corroborated by BER tests, with Sniff test eliminates last usual suspect	
11/5/18	MPO briefs NASA HQ and Executive Council	
11/8/18	MRO Implements Corrective Action	
11/26/18	InSight lands successfully, MRO open-loop recording successful	

Background: Mars Relay Network

Odyssey

NASA
- Launched 2001

Orbit:
- 400km sun-synch
- 93° inclination

Deep Space Link:
- X-band
- 15W SSPA
- 1.3m HGA

Prox Link:
- CE-505 (dual-string)
- Single UHF Channel
- Fixed Data Rates
  - 8, 32, 128, 256kbps return link
- Residual Carrier
- ½ rate Conv. Coding

Mars Express

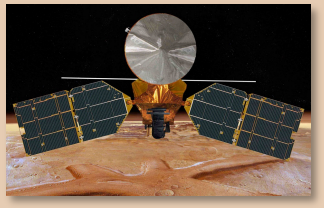
ESA
- Launched 2003

Orbit:
- 330x10530km elliptical
- 87° inclination
- Non-sun-synch

Deep Space Link:
- X-band
- 65W TWTA
- 1.65m HGA

Prox Link:
- Melacom (QinetiQ)
- Single UHF Channel
- Fixed Data Rates
  - 2, 4,…, 128kbps return link
- Residual Carrier
- ½ rate Conv. Coding

MRO



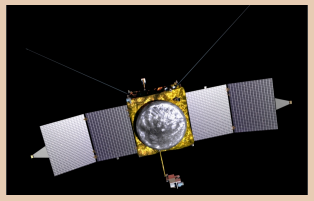
NASA
- Launched 2005

Orbit:
- 255x320km sun-synch
- 93° inclination

Deep Space Link:
- X-band
- 100W TWTA
- 3m HGA

Prox Link:
- Electra (dual-string)
- Freq-Agile (390-450 MHz)
- Adaptive Data Rates
  - 1, 2, 4,…, 2048kbps return link
- Suppressed & Residual Carrier
- ½ rate Conv. Coding
- Open-loop recording

MAVEN



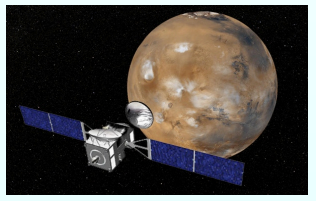
NASA
- Launched 2013

Orbit:
- 150x6200km elliptical
- 74° inclination
- Non-sun-synch

Deep Space Link:
- X-band
- 100W TWTA
- 2m HGA

Prox Link:
- Electra (single-string)
- Freq-Agile (390-450MHz)
- Adaptive Data Rates
  - 1, 2, 4,…, 2048kbps return link
- Suppressed & Residual Carrier
- ½ rate Conv. Coding & LDPC
- Open-loop recording

TGO



ESA
- Launched 2016

Orbit:
- (eventually) 400km circular
- 74° inclination
- Non-sun-synch

Deep Space Link:
- X-band
- 65W TWTA
- 2.2m HGA

Prox Link:
- Electra (dual-string)
- Freq-Agile (390-450MHz)
- Adaptive Data Rates
  - 1, 2, 4,…, 2048kbps return link
- Suppressed & Residual Carrier
- ½ rate Conv. Coding & LDPC
- Open-loop recording

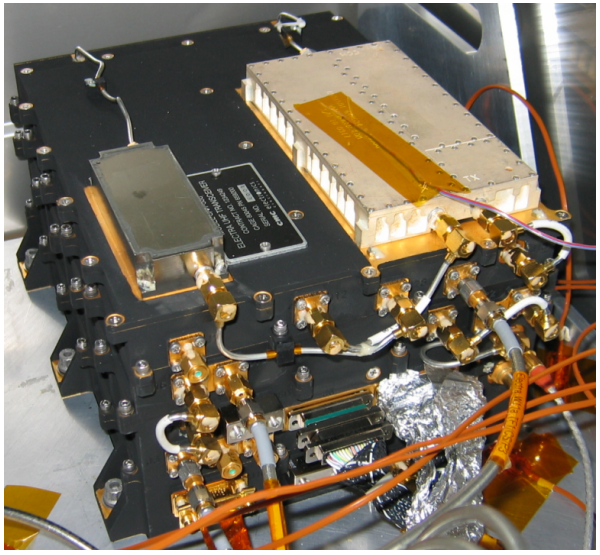
MRO is an aging orbiter, and while newer orbiters can record EDL telemetry, MRO could readily be phased for InSight EDL

Background: MRO Electra Radio

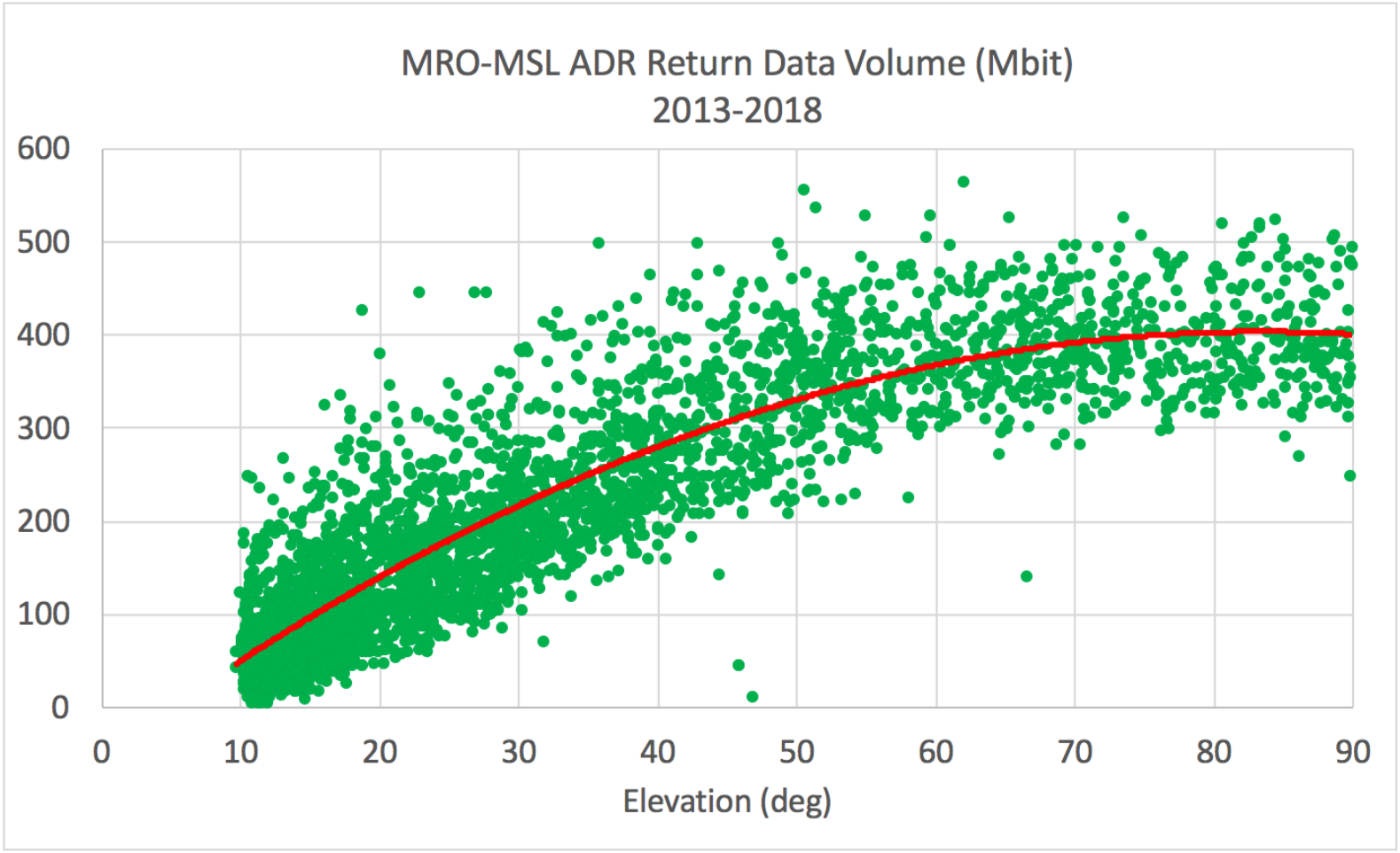
- **Software defined UHF transceiver**
- **Dual-string, single UHF antenna with switch**
  - Side B Electra never exercised in flight
- **Redundant ultra-stable oscillator (USO) frequency reference**
- **Freq-Agile (390-450 MHz)**
  - Frequencies selected ahead of pass (does not hop)
  - Normally, return link operates @ 401 MHz
  - MRO used 390 MHz with MSL because of EMI
- **Fixed and Adaptive Data Rates (ADR)**
  - 32 - 2048 kbps return link, adapting to available SNR
  - MSL usually operates with ADR on return link
- **Bitstream (Raw) "no protocol" mode**
- **Suppressed & residual carrier modulation**
- **½ rate convolutional coding**
- **Open-loop recording**
  - 150 ksamples/s : 150kHz bandwidth
  - Used for EDL, usually 8 kbps conv-coded residual carrier
  - Used also for 'sniffing' electromagnetic interference
- **Bit Error Rate Loopback**
  - Self-test that is sensitive to received noise and interference

UHF Antenna

MRO Electra

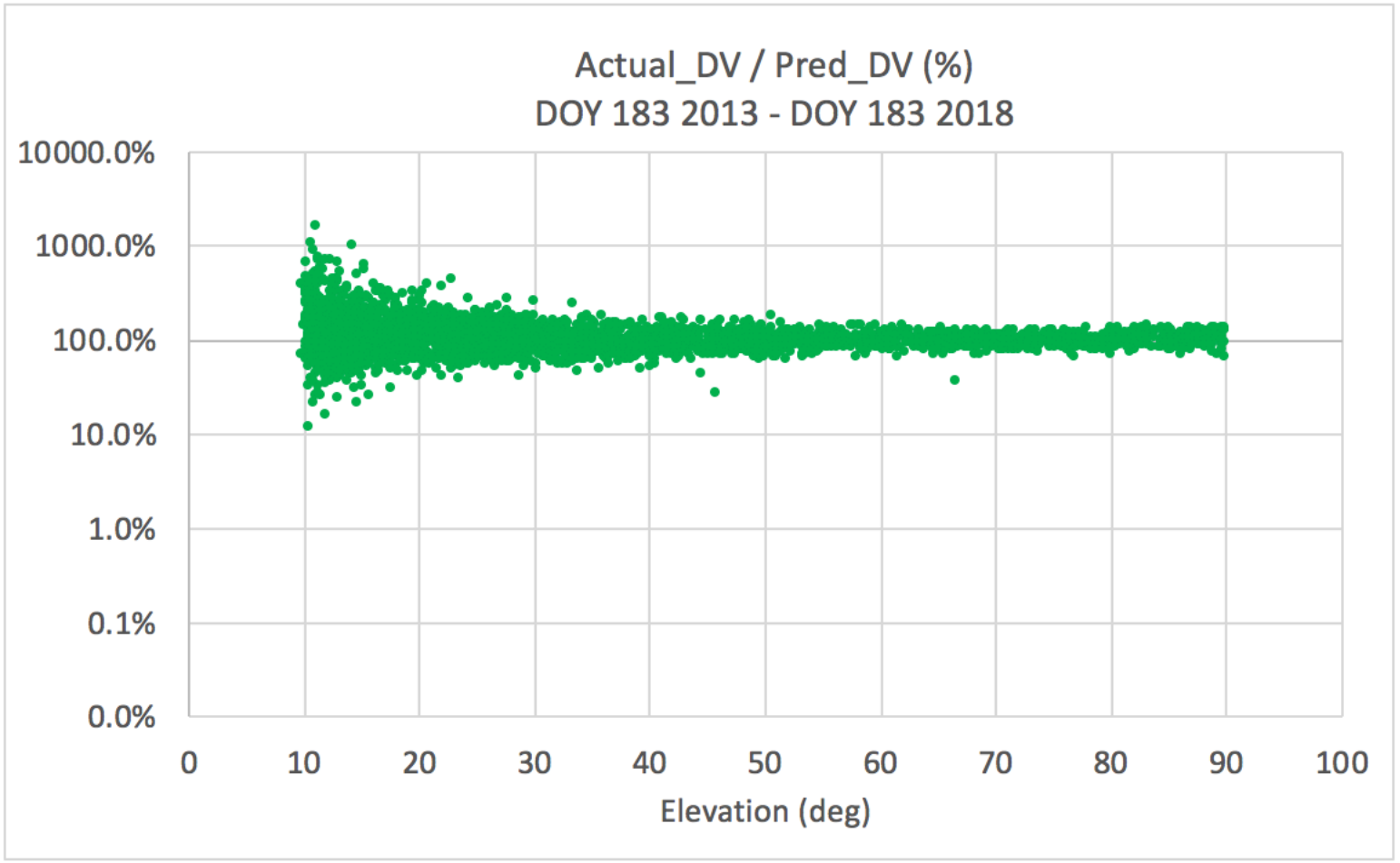


MRO-MSL Relay Performance



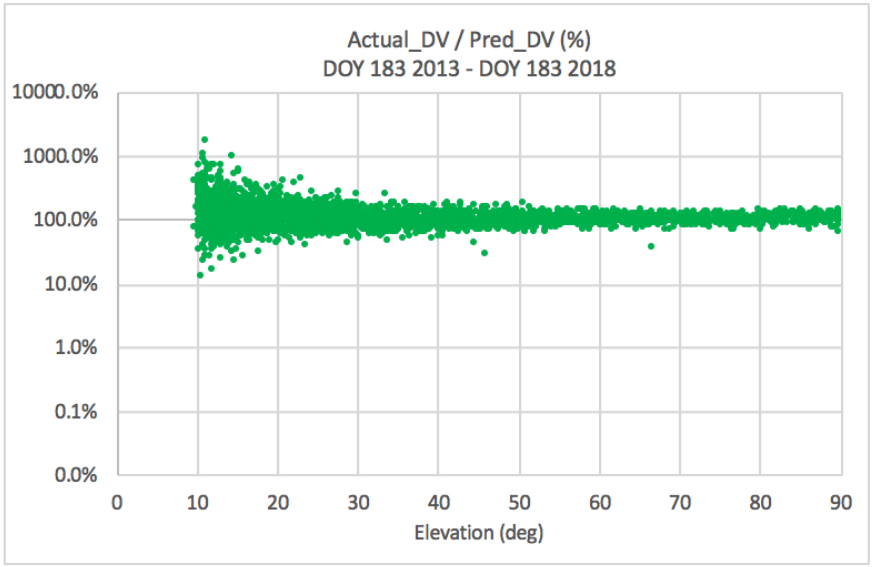
- **Obvious:** performance improves with maximum orbiter elevation angle
- **Not so obvious:** lower elevation passes tend to have larger variability
- **Nice:** a simple polynomial fit can be used to predict data volume (DV) performance

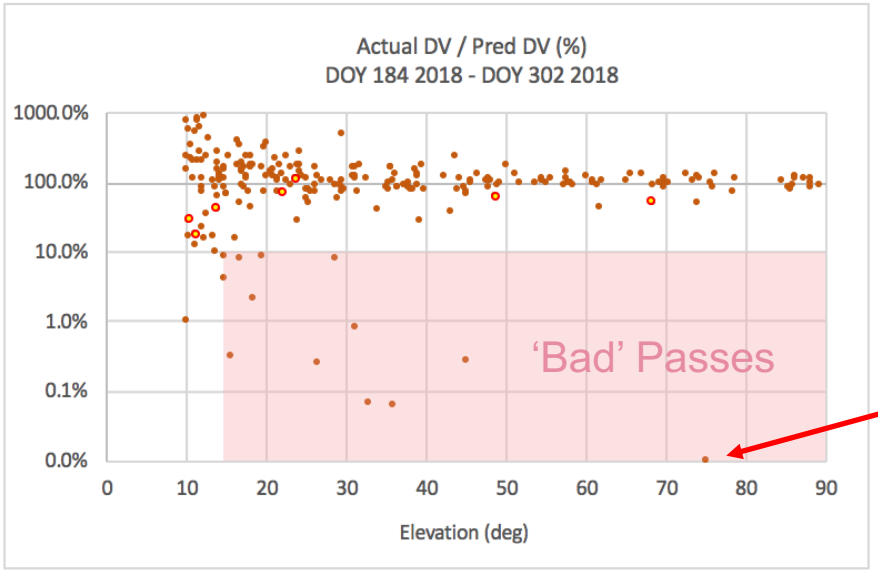
MRO-MSL Actual v. Predicted DV



- **Obvious:** relative performance is more variable at lower elevation angles
- **Interesting:** In 5 years of MRO-MSL relay operations (excluding known anomalies), actual DV never falls below 10% of predicted DV

Enter the Anomaly





- Starting DOY 184 (7/3/18), MRO-MSL DV return starts to drop below 10% of predicts
- To focus our investigation, we define 'bad' passes as falling below the 10% threshold, but exclude passes below 15 deg elevation because of the high variability of these passes
  - *Even though there is evidence that low elevation passes are being hit by anomaly*
- Later, we see signs of anomaly hitting passes outside of the 'bad zone'
- MRO_MSL_2018_280_03 (10/7/18) returned no data on a 75 deg pass
  - This really got people's attention..

Pass Summary: July 3 – October 9 2018

Overflight	Date	Predict (Mb)	Actual (Mb)	Act/Pred (%)	Max Elev (deg)	Az	Mode
TGO_MSL_2018_184_01		828	677	82%	60	N-W-S	Ch0 ADR 32-2048
MRO_MSL_2018_184_01		223	90	40%	34	N-E-S	Ch2 ADR 32-2048 Relay Quiet
MRO_MSL_2018_184_03	7/3/2018	89	8	9%	20	S-E-N	Ch2 ADR 32-2048 Relay Quiet
MRO_MSL_2018_185_01		52	8	15%	16	N-E-S	Ch2 ADR 32-2048 Relay Quiet
MRO_MSL_2018_186_03	7/5/2018	56	0.2	0.3%	16	N-W-S	Ch2 ADR 32-2048 Relay Quiet
MVN_MSL_2018_186_04		387	351	91%	44	N-E-S	Ch0 ADR 32-2048
MRO_MSL_2018_187_01	7/6/2018	157	0.4	0.3%	27	S-W-N	Ch2 ADR 32-2048 Relay Quiet
MRO_MSL_2018_187_03	7/6/2018	190	0.1	0.1%	33	N-W-S	Ch2 ADR 32-2048 Relay Quiet
MRO_MSL_2018_188_01		357	163	46%	62	S-W-N	Ch2 ADR 32-2048 Relay Quiet
MRO_MSL_2018_188_02		421	327	78%	79	N-W-S	Ch2 ADR 32-2048 Relay Quiet

Overflight	Date	Predict (Mb)	Actual (Mb)	Act/Pred (%)	Max Elev (deg)	Az	Mode
MRO_MSL_2018_259_02		217	192	88%	35	S-E-N	Ch2 ADR 32-2048 Relay Quiet
MRO_MSL_2018_260_02	9/17/2018	179	15	8%	29	N-E-S	Ch2 ADR 32-2048 Relay Quiet
MRO_MSL_2018_260_04	9/17/2018	98	8	8%	17	S-E-N	Ch2 ADR 32-2048 Relay Quiet
TGO_MSL_2018_261_02		788	793	101%	48	N-W-S	Ch0 ADR 32-2048
MRO_MSL_2018_261_02		75	8	10%	14	N-E-S	Ch2 ADR 32-2048 Relay Quiet
MRO_MSL_2018_262_01		84	58	69%	15	S-W-N	Ch2 ADR 32-2048 Relay Quiet
MRO_MSL_2018_262_03		139	244	176%	18	N-W-S	Ch2 ADR 32-2048 Relay Quiet

Overflight	Date	Predict (Mb)	Actual (Mb)	Act/Pred (%)	Max Elev (deg)	Az	Mode
MRO_MSL_2018_270_01		308	354	115%	58	S-E-N	Ch2 ADR 32-2048 Relay Quiet
TGO_MSL_2018_270_03		668	568	85%	34	N-W-S	Ch0 ADR 32-2048
MRO_MSL_2018_270_03	9/27/2018	266	20	8%	46	N-E-S	Ch2 ADR 32-2048 Relay Quiet *
MRO_MSL_2018_271_01		157	84	53%	25	S-E-N	Ch2 ADR 32-2048 Relay Quiet
MRO_MSL_2018_271_03		128	158	124%	21	N-E-S	Ch2 ADR 32-2048 Relay Quiet
MRO_MSL_2018_272_01		61	14	24%	12	S-E-N	Ch2 ADR 32-2048 Relay Quiet
MRO_MSL_2018_272_04		105	123	117%	12	N-W-S	Ch2 ADR 32-2048 Relay Quiet
MRO_MSL_2018_273_03		161	94	58%	25	N-W-S	Ch2 ADR 32-2048 Relay Quiet
MRO_MSL_2018_274_01		278	192	69%	45	S-W-N	Ch2 ADR 32-2048 Relay Quiet
MRO_MSL_2018_274_02		313	445	142%	58	N-W-S	Ch2 ADR 32-2048 Relay Quiet
MRO_MSL_2018_275_01		362	191	53%	74	S-E-N	Ch2 ADR 32-2048 Relay Quiet
TGO_MSL_2018_275_04		825	822	100%	61	N-W-S	Ch0 ADR 32-2048
MRO_MSL_2018_275_02		329	316	96%	58	N-E-S	Ch2 ADR 32-2048 Relay Quiet
MRO_MSL_2018_276_03		165	119	72%	26	N-E-S	Ch2 ADR 32-2048 Relay Quiet
MRO_MSL_2018_276_05	10/3/2018	202	2	0.8%	31	S-E-N	Ch2 ADR 32-2048 Relay Quiet
MRO_MSL_2018_277_01		83	8	9%	15	S-E-N	Ch2 ADR 32-2048 Relay Quiet
MRO_MSL_2018_277_03		61	10	16%	12	N-E-S	Ch2 ADR 32-2048 Relay Quiet
MRO_MSL_2018_278_02		99	50	50%	17	S-W-N	Ch2 ADR 32-2048 Relay Quiet
MRO_MSL_2018_278_03		135	198	146%	21	N-W-S	Ch2 ADR 32-2048 Relay Quiet
MRO_MSL_2018_279_01	10/6/2018	230	0.2	0.1%	36	S-W-N	Ch2 ADR 32-2048 Relay Quiet
TGO_MSL_2018_279_04	10/6/2018	431	545	126%	24	N-W-S	Ch0 ADR 32-2048
MRO_MSL_2018_279_02	10/6/2018	261	1	0.3%	45	N-W-S	Ch2 ADR 32-2048 Relay Quiet
MRO_MSL_2018_280_03	10/7/2018	362	0	0.0%	75	N-E-S	Ch2 ADR 32-2048 Relay Quiet
MRO_MSL_2018_281_02		245	198	81%	39	S-E-N	Ch2 ADR 32-2048 Relay Quiet
MRO_MSL_2018_281_04		203	259	128%	31	N-E-S	Ch2 ADR 32-2048 Relay Quiet
MVN_MSL_2018_282_01		18	20	109%	17	S-E	Ch0 ADR 32-2048

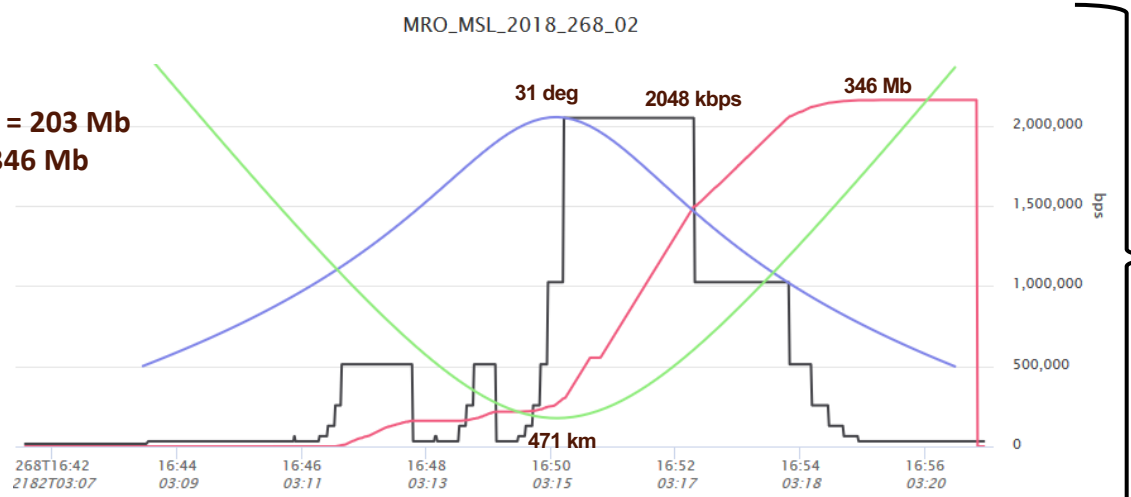
- Bad passes (**DV<10%, EL>15°**) started early July 2018 and have occurred sporadically until the first week of October 2018
  - Long periods between bad passes (as much as 73 days)
- Bad passes tend to occur more frequently at low max. elevation angles but have occurred at max. elevation up to 75 deg
- Bad passes are often bracketed by Good Passes (DV>75%) or Marginal Passes (between good and bad) on same day
  - Some evidence of bad pass clustering
- No obvious correlation with MRO passing East or West of MSL
- No correlation with MSL RCE swap (DOY 276)
- MAVEN & TGO passes around time of MRO bad passes show no signs of anomaly

* MSL Reset

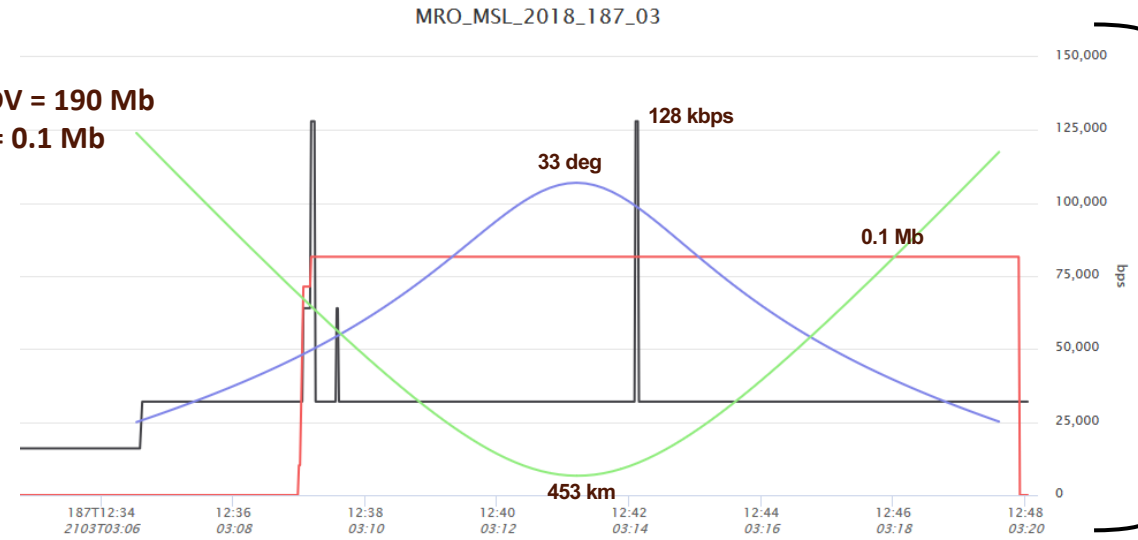
Telemetry from Good and Bad Passes

Passes with similar geometry exhibiting good and bad performance

Good Pass
Predicted DV = 203 Mb
Actual DV = 346 Mb



Bad Pass
Predicted DV = 190 Mb
Actual DV = 0.1 Mb



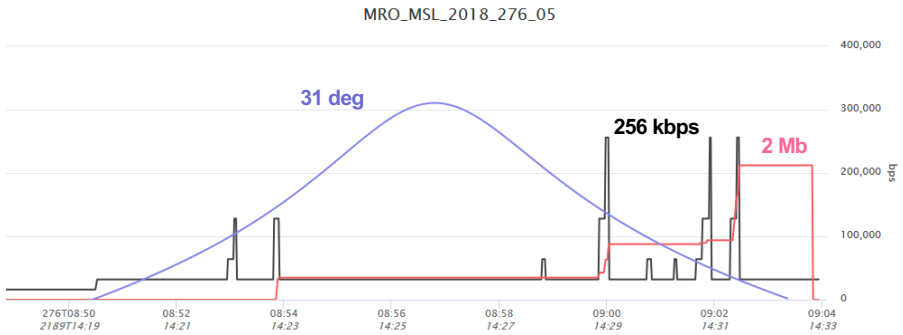
Good

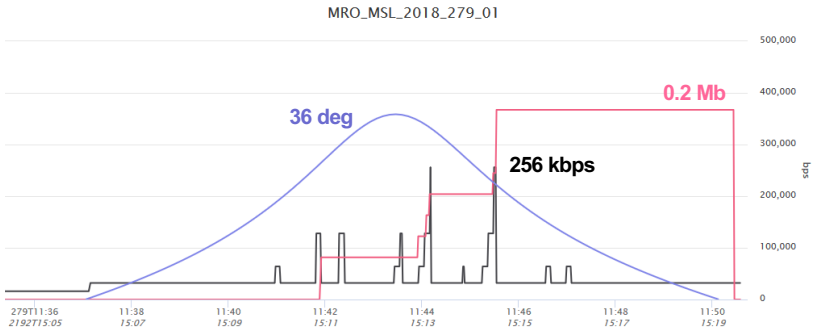
- Adaptive data rate 'stair-cases' as link conditions vary
- Return data volume gradually ramps up across pass
- Other telemetry variables such as carrier unlock, bad CRC, out-of-sequence frames (not shown) generally exhibit low counts

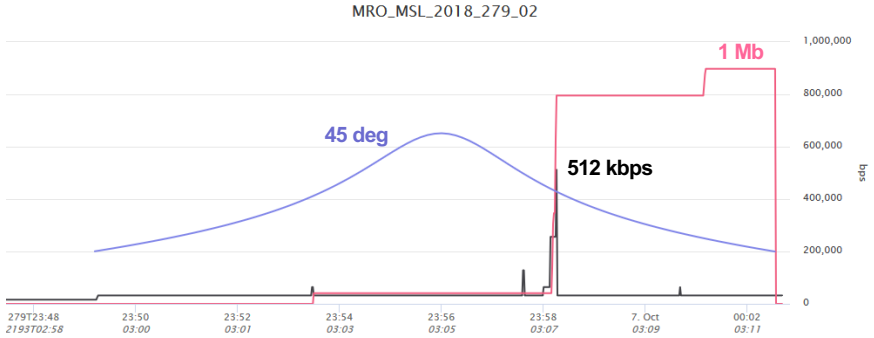
Bad

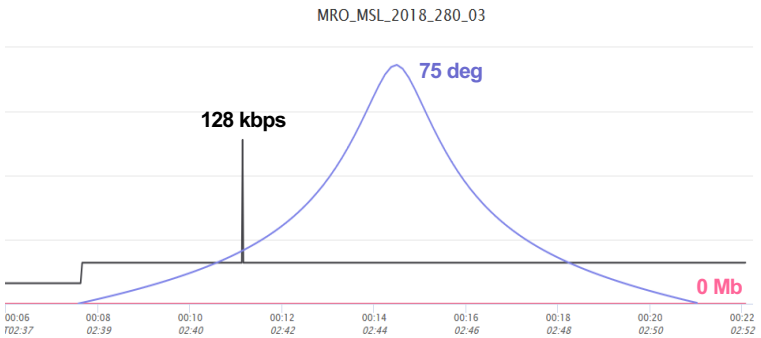
- Adaptive data rate is impulse like, link drops precipitously
- Return data volume increments sporadically
- Generally, high counts of carrier unlock, bad CRC, out-of-sequence frames

More Bad Pass Rate / DV Signatures





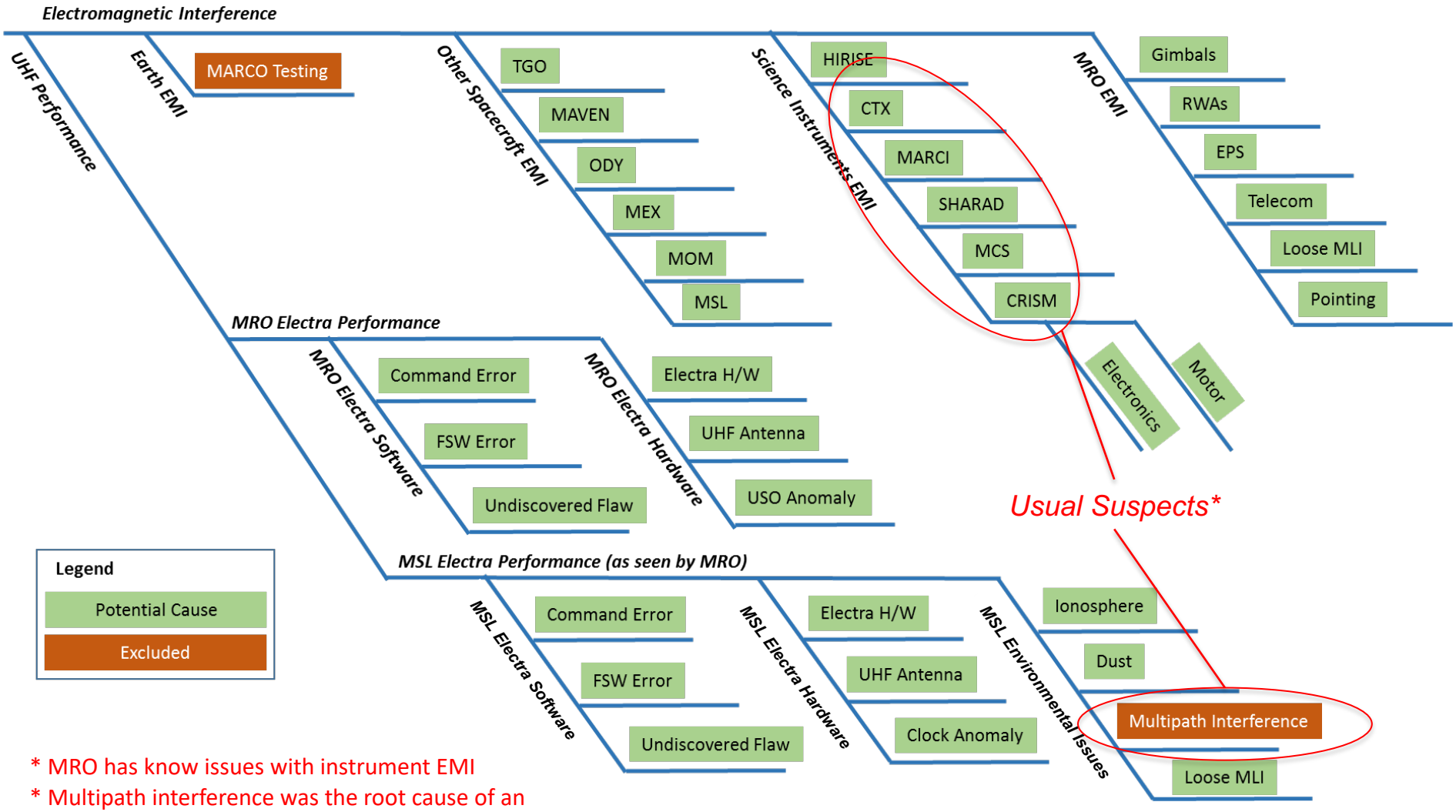




- Sporadic link closure with max rates varying between 128 kbps and 1024 kbps
- Precipitous link drop (loss of lock and often several rehails before link closes again)
  - *No graceful downward transition between data rates*
- Return-link data generally flows on a subset of the instances when link is closed
  - *In one case no data was returned*
- In all cases the file_00 was transmitted on the forward link
- Not shown: increased counts of carrier unlock, bad CRC frames, out of sequence frames

All The Suspects (as of 10/10/18)

MRO Fishbone Diagram v1, Courtesy of Bruce Waggoner

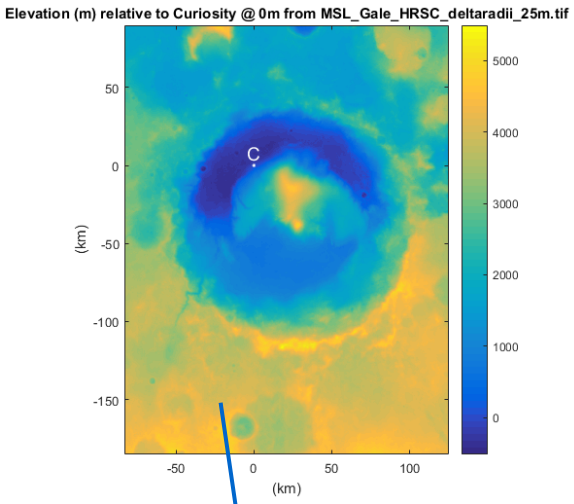


* MRO has know issues with instrument EMI
* Multipath interference was the root cause of an MRO-MSL anomaly investigation in 2012

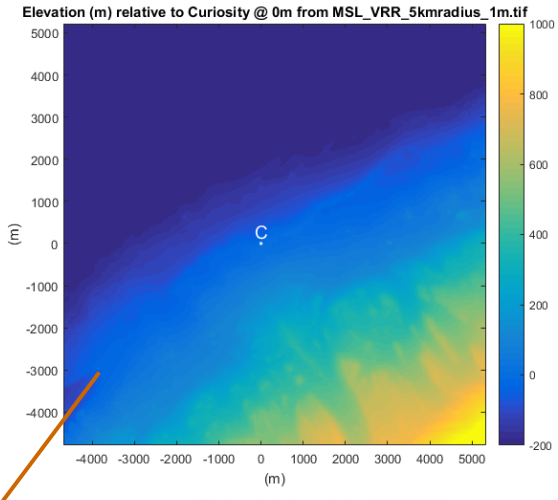
Investigating Terrain Effects

- *UHF transmission is blocked when orbiter elevation drops below terrain mask*
- *Multipath fading is prevalent at up to 25° above terrain mask*

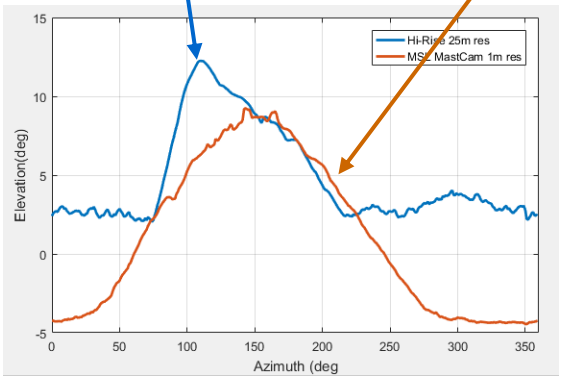
HiRise

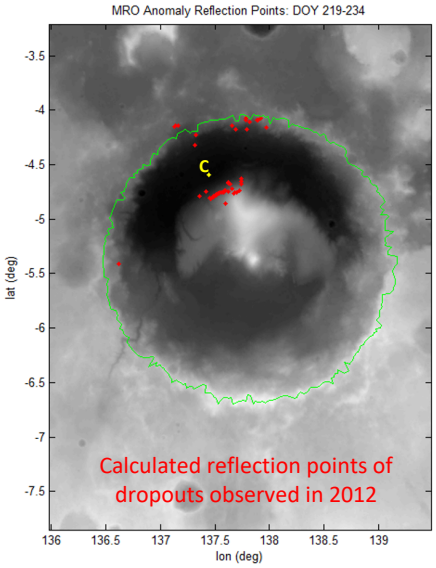


MastCam



Terrain Mask





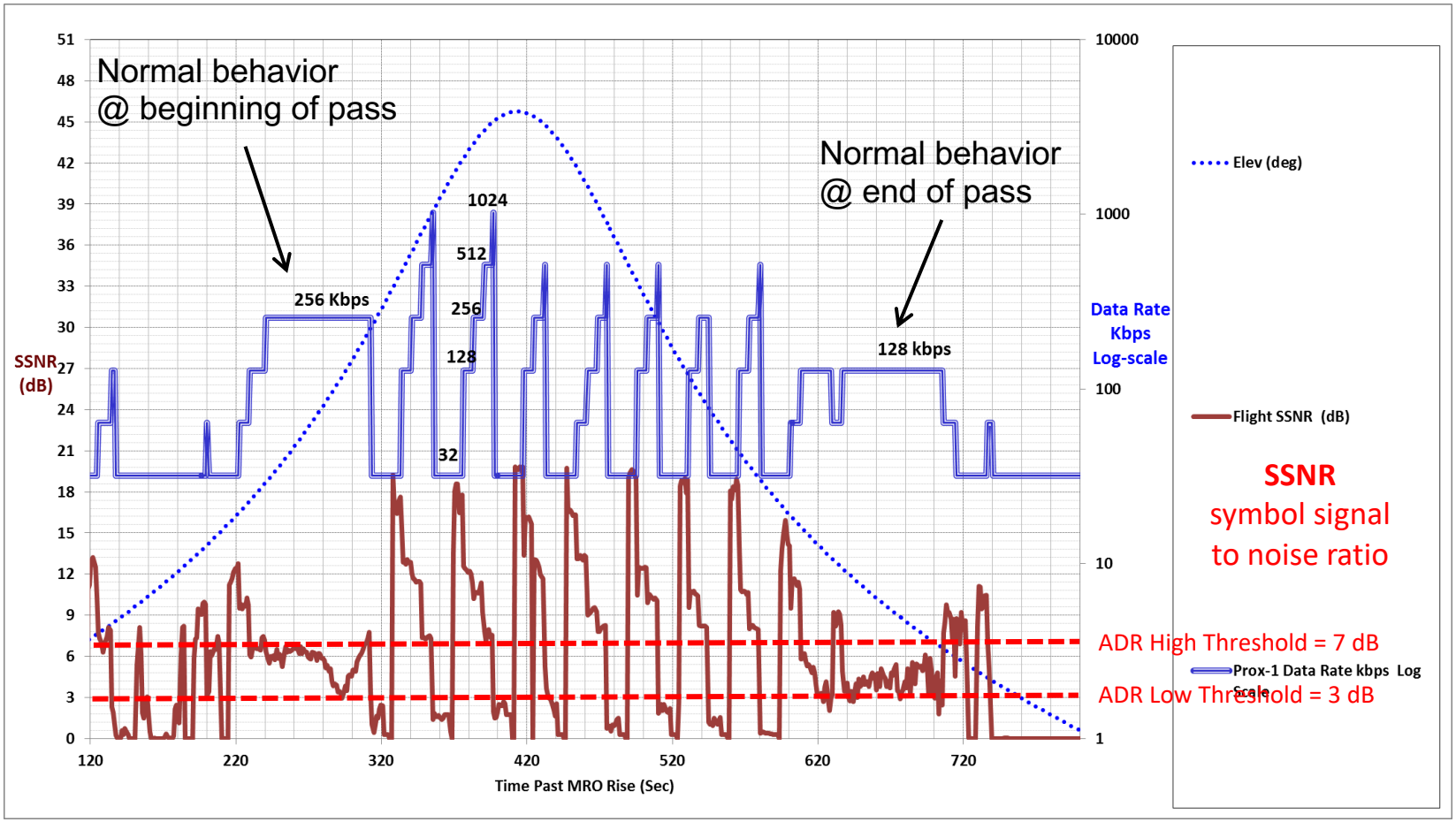
- Multipath interference was the root cause of anomalous dropouts observed shortly after MSL landed in 2012
- Initially, terrain effects were suspected for causing the first bad passes (starting DOY 184 2018)
  - Terrain blocking, due to rover location
  - Multipath interference
- Because MSL had moved significantly compared to when the old terrain map was generated (years ago), a new terrain map was generated for the new rover position at Sol 2102 (DOY 186 2018), using both HiRise and MSL MastCam digital elevation maps
- Terrain mask has not significantly changed over several years of MSL operations (eliminating terrain blocking as root cause)
  - Exception of traversing Murray Buttes, 2017
- Large number of overflights with MRO and other orbiters, in tandem with the fact the anomaly can persist for many minutes and can occur at high elevation angles eliminates multipath interference as root cause (multipath fading is ephemeral and low elevation)

Could it be the Dust Storm?

- Earlier bad passes occurred at height of Mars planet encircling dust storm (roughly July 2018)
- At the height of the dust storm (early on in the investigation) the following were looked into..
  - Attenuation due to dust?
    - Dust particle diameter ~1.5 micron provides virtually no attenuation at 401 MHz
  - MRO Ephemeris – could the dust be slowing MRO down?
    - Density scale factor at MRO rose to 1.4 (from about 1)
    - The impact on ephemeris was assessed through GTP calculations using predicted and reconstructed orbits and found to be negligible
  - Changes to Ionosphere?
    - MAVEN Project held a special session (9/21/18) to discuss observations taken by MRO and MAVEN during dust storm
    - MAVEN PI Bruce Jakosky and MRO Scientist Rich Zurek both concur that none of the observations suggests significant changes to ionosphere due to the dust storm
- **Dust storm abated as bad passes continued, eliminating dust as a possible cause**

EMI (There's an Unlimited Supply)

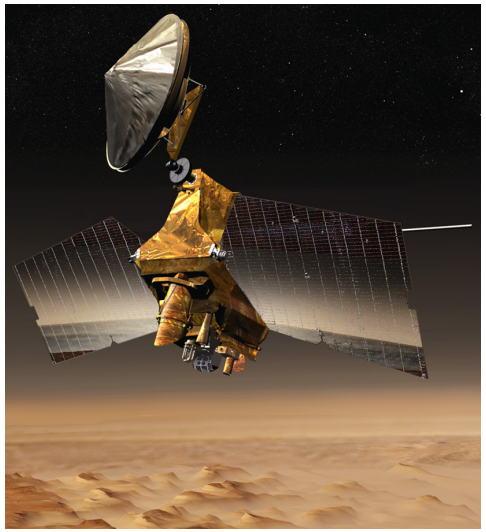
- MRO_MSL_2014_161_03 was run with ADR on Channel 0 (401. MHz) to assess potential performance for ExoMars EDM
- MRO was in *Relay Quiet Mode*: instruments on, including known EMI culprit CRISM (on but not active)
- ADR algorithm broke down due to the corruption of SSNR estimator by CRISM noise for rates above 256 kbps
- Signature is similar to more recent anomalous passes with consequent low data volume (about 1/10 of typical)
- Given the above, EMI became prime suspect, spurring a series of investigations focused on proving the EMI theory

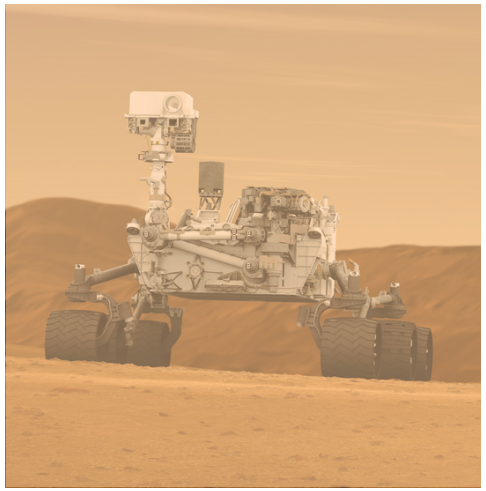


MSL as an In-Situ Testbed

MSL engaged in a number of off-nominal relay activities in support of the anomaly investigation

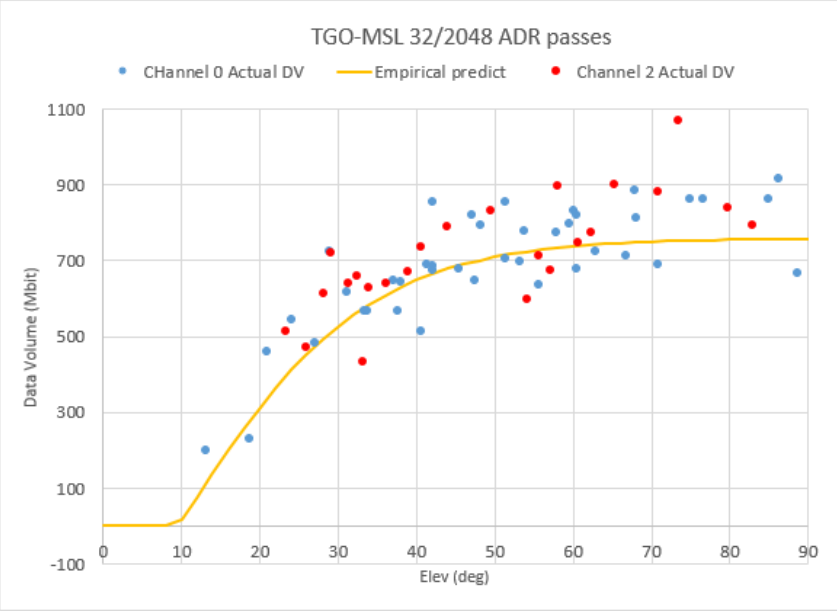
- 10/13/18: Changed from Channel 2 (390 MHz) to Channel 0 (401MHz) with instruments still on
  - Goal was to assess impact on anomaly Channel 0, which would be used for InSight EDL
  - ADR limited to 256kbps, residual carrier (not a mode normally used by MSL)
- 10/15/18: Saw two marginal DV passes (at low elevation angles), switched instruments off (except HiRise)
  - Increased ADR rate to 1024k since interference from CRISM no longer present
- 10/28/18 Switched modulation to suppressed carrier 10/28/18
  - ADR thresholds are not optimized for RC and in some instances were causing link drops
- 10/16/18 – 10/29/18 No bad passes (except one low DV pass at 10 deg elevation on 10/21/18)
- **10/30/18 First bad pass in 2 weeks (actual = 1% of predict, elevation = 18 deg)**
- 10/31/18 Low elevation passes (< 15 deg) begin executed at 8kbps fixed data rate
  - Some low DVs but no bad passes or conclusive evidence of anomaly
- 11/03/18 executed large forward link file transfer
  - No evidence of anomaly
- 11/04/18 Transmitted in “raw” data mode (no forward link / acknowledgements)
  - Goal was to isolate Prox1 protocol
  - No evidence of anomaly
- 11/07/18 Performed open loop recording with MRO at 8kbps raw data transmission
  - Nominal EDL configuration to test preparedness for InSight landing
  - No evidence of anomaly





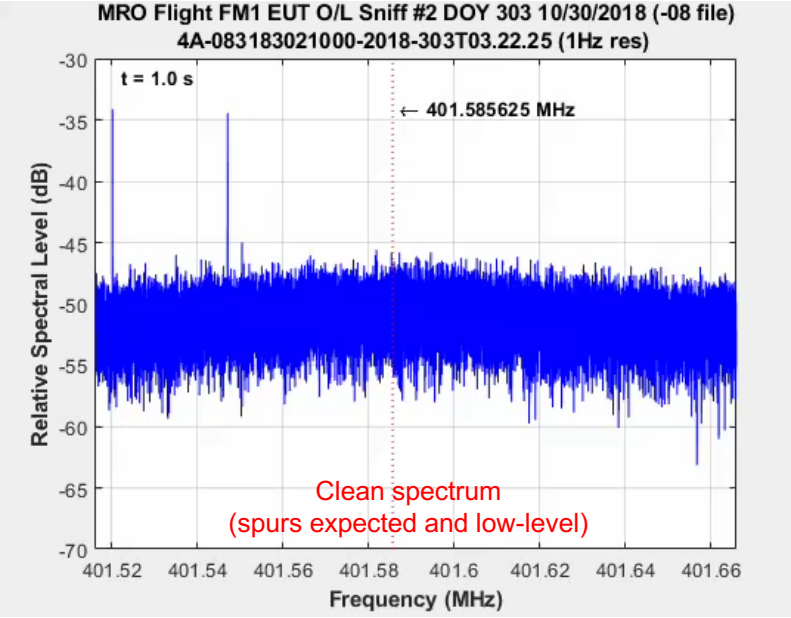
Could It Be MSL?

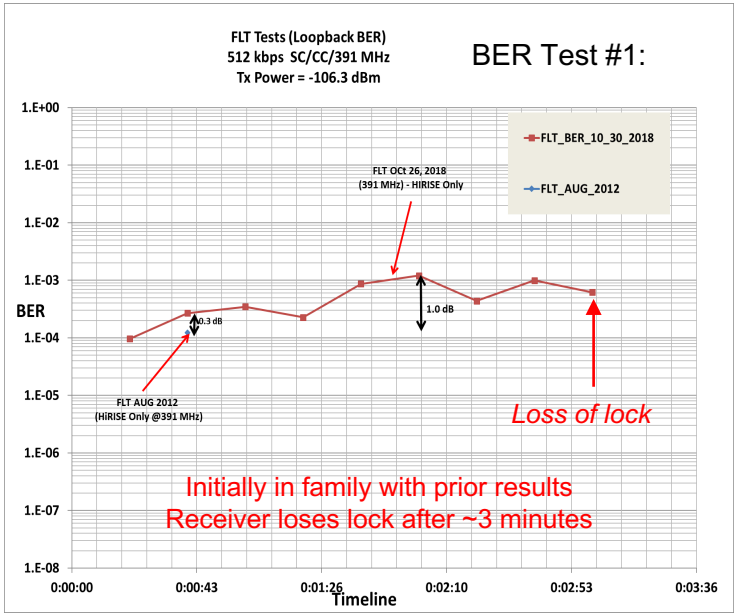
- While thought unlikely, if the root cause were MSL, then it should be seen in other orbiter's performance (TGO and MAVEN), which exclusively operate on Channel 0
- Starting 10/13/18 for MAVEN and 10/21/18 for TGO, MSL passes were scheduled on Channel 2 instead of Channel 0
- No anomalous returns were seen in 41 Channel 2 ADR passes with these two orbiters
- Additionally, prior to the switch to Channel 2, no anomalous returns were seen in 76 Channel 0 ADR passes, eliminating MSL as the root cause
- For MAVEN, Channel 2 DV performance on average was the same as Channel 0
- For TGO, Channel 2 DV performance showed a noticeable improvement over Channel 0 of about 13%



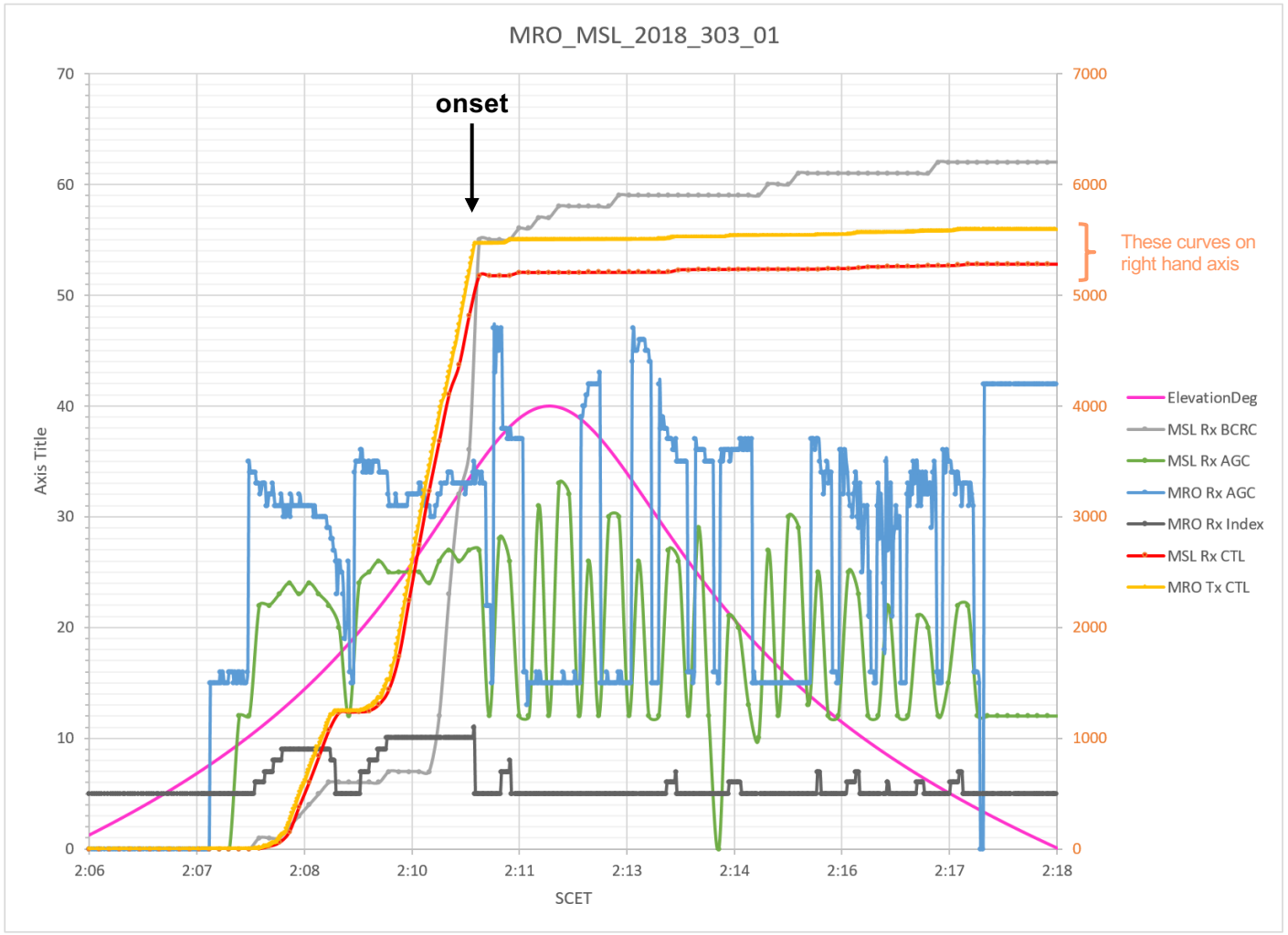
Loopback and Sniff Tests

- Going into the last week of October 2018, EMI was the leading suspect
- On 10/23/18, Ricardo Mendoza noticed that both the forward link and return link of a bad pass 2 weeks earlier were being affected by the anomaly, casting doubt on the EMI theory
  - EMI from MRO should only impact the return link
- MRO started implementing bit error rate loopback tests and EMI sniff tests staring 10/24/18, run as a "3-car train": 2-minute Sniff Test, Relay Pass, 2 BER tests
  - BER Test #1: 13 minutes @ 512kbps coded suppressed carrier on Channel 0
  - BER Test #2: 13 minutes @ 256kbps coded residual carrier on Channel 0
- Initial results showed no evidence of EMI, then something remarkable happened on 10/31/18 – a pass appeared to be hit by the anomaly mid-pass
  - The Sniff data were clean, the BER data from the first test showed evidence of the anomaly, inconsistent with EMI



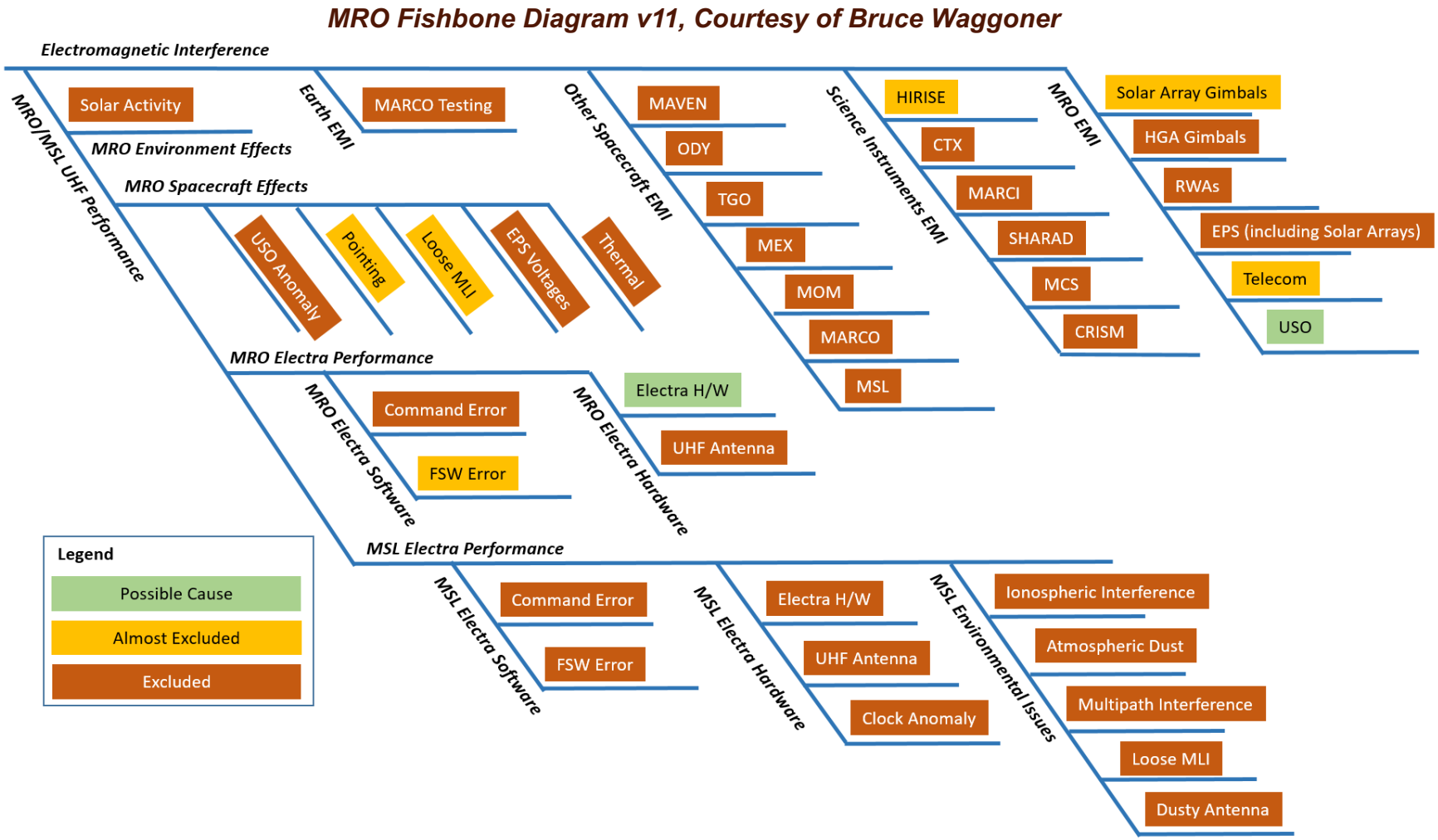


Caught In The Act..



- Telemetry from suggests that an anomaly occurs about 3 minutes into the pass
- Both the forward-link and the return-link (not shown) are reporting bad CRC frames, with almost no data being returned after the apparent onset of the anomaly
- Signal levels are adequate to support the link

Back to the Fishbone

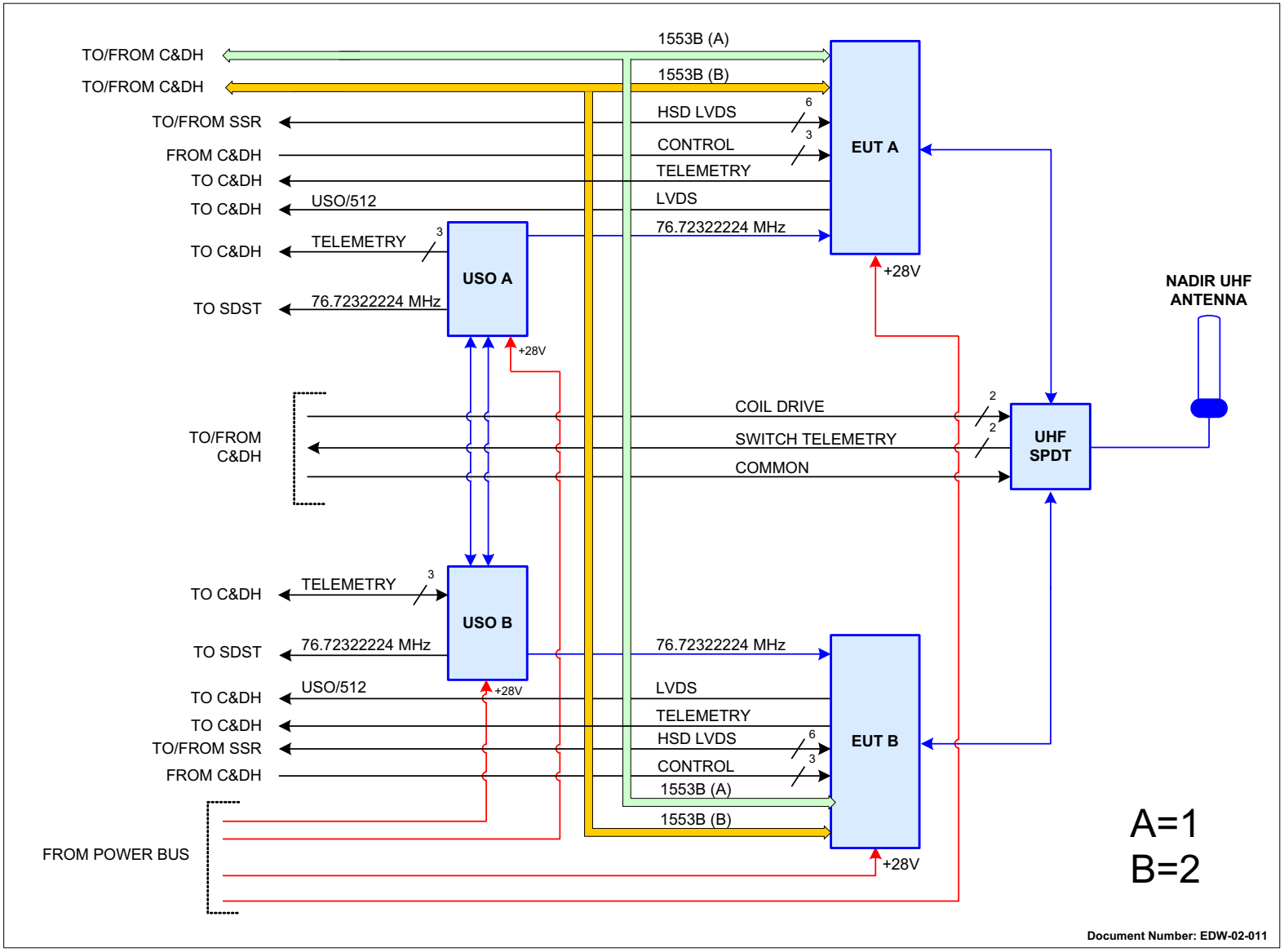


- In parallel with the Electra-oriented investigation, MRO team was working to eliminate many of the potential non-Electra causes
- Instruments were (mostly) eliminated since anomalies had occurred when they were off
- Going into November 2018, there were two remaining 'prime' suspects: MRO Electra and the Ultra Stable Oscillator (USO)

Ultra Stable Oscillator (USO)

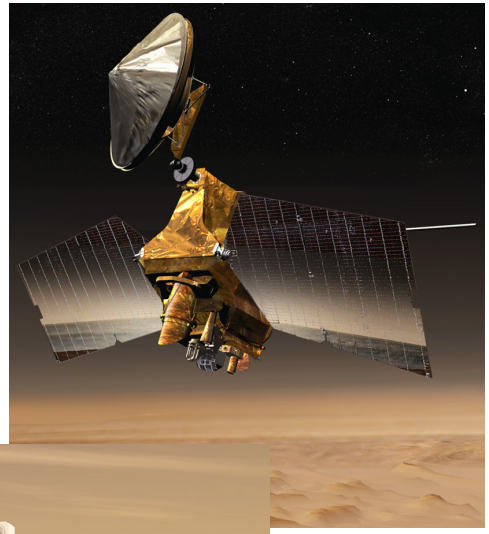
- MRO has redundant cross-strapped USOs that provide the timing reference for Electra as well as (optionally) the X-band comm system
- The USO quickly became the prime suspect as it could readily account for forward link and return link being simultaneously impacted
- Additionally, the USO had a 'past record' that implicated it as the cause of the anomaly
- Significantly increased Doppler noise was observed on USO 1 in 2012, 2017, and during safemode in 2018
  - As a result of the 2017 incident where DSN was unable to lock up, the X-band frequency reference was switched from USO 1 to the auxiliary oscillator (rather than switch to USO 2)
  - Estimated USO frequency shift was ~5Hz, too low to impact Electra
  - USO 2, like Electra 2, had *never* been exercised in flight
- 10/3/18: DSN performed an open-loop recording of X-band downlink with frequency reference switched back to USO 1
  - Ground receivers could not lock up on the signal, further implicating USO 1
  - Test was rescheduled for 11/5/18 but was not performed
- Decision to swap to USO 2 was deliberated – some risk that USO 2 would be bad and the switch back to USO 1 could fail (versus accepting continued occasional bad performance on USO 1)
  - Flight rule prohibited cross-strapping USOs because fault protection was not fully implemented. This restricted operation of Electra 1 to USO 1 and Electra 2 to USO 2 (not allowed: Electra 1 to USO2)
  - Switching to Electra 2 more onerous as it involved side swap on C&DH, switch to HiRise 2 and Solid State Recorder 2, and updating Electra software/firmware
- 11/5/18: NASA HQ and Executive Council were briefed, decision was made to swap to USO 2 11/7/18
- **Post USO swap, relay passes have been anomaly free**
  - Repeat of the DSN open loop recording showed X-band performance to be nominal. X-band remains on USO 2

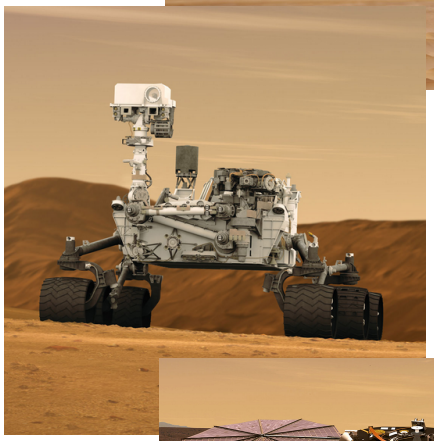
Electra Block Diagram

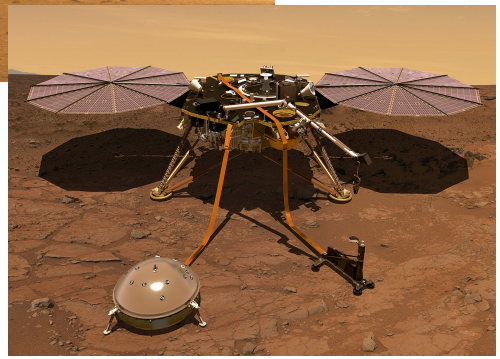


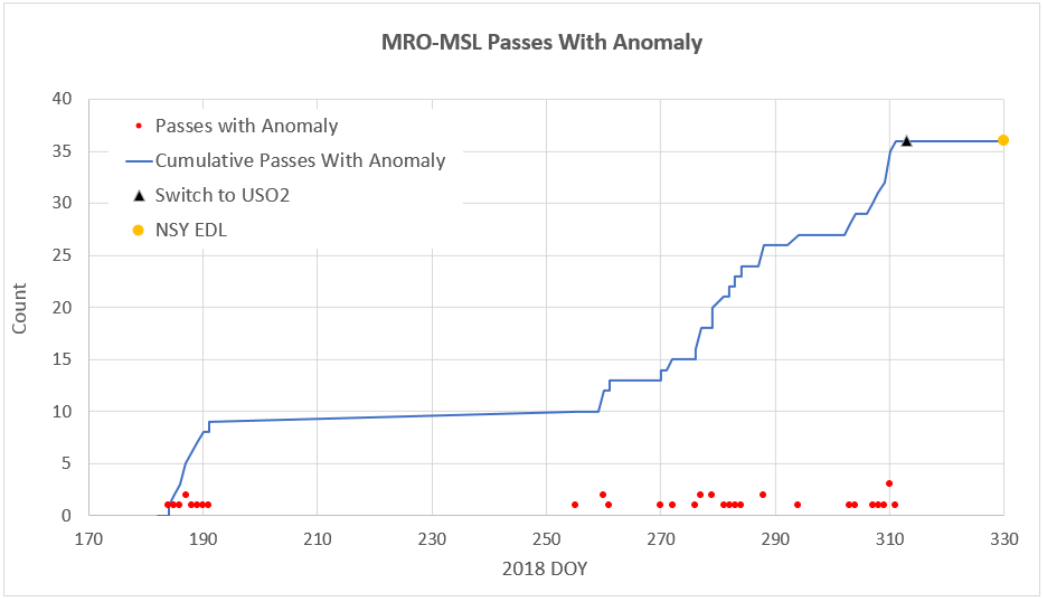
Summary

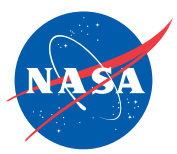
- MRO started experiencing *bad* passes with MSL starting July 2017
- Teams from MRO, Electra and elsewhere had to come together quickly in the roughly 6 weeks before InSight EDL to correct this problem
- The *usual* suspects (multipath and EMI) turned out to be innocent of the crime in this case – ultra stable oscillator turned out to be the culprit
- MRO open-loop recording of InSight EDL was successful
- Subsequent MRO support of MSL/NSY surface operations has been anomaly free and slightly exceeding prior (MSL) data volumes











Questions